STICTION ALLEVIATION USING PASSIVATION LAYER PATTERNING

TECHNICAL FIELD

The invention relates to stiction alleviation, and more particularly to stiction alleviation using a patterned passivation layer.

BACKGROUND OF THE INVENTION

Micro-Electro-Mechanical System (MEMS) devices find applications in a variety of fields, such as communications, sensing, optics, micro-fluidics, and measurements of material properties. In the field of communications, variable MEMS capacitors are used in tunable RF filter circuits. The MEMS capacitors offer several advantages over solid state varactor diodes, including a higher on/off capacitance ratio and a higher Quality (Q) factor. In addition, MEMS devices offer greater linearity compared to their solid state counterparts, which reduces intermodulation products when used in Radio Frequency (RF) applications.

Many of these MEMS devices comprise a beam or microstructure suspended above a substrate by one or more supports. In a variable MEMS capacitor, for example, the beam may be suspended above a bottom electrode on the substrate to form a capacitor with the beam acting as the top electrode. The capacitance of the variable MEMS capacitor is varied by establishing an electrostatic force between the beam and the bottom electrode. The electrostatic force bends the beam relative to the bottom electrode, thereby changing the gap between the beam and the bottom electrode and, therefore, the capacitance of the MEMS capacitor.

A problem in MEMS devices is permanent adhesion of the beam or microstructure to the underlying substrate. This phenomenon is commonly referred to as "stiction". Stiction typically

occurs when a beam or other microstructure is brought into intimate contact with the substrate. Once in contact, adhesion forces, e.g., Van der Waals force and/or hydrogen bonding, on the surface of the substrate exceed the elastic restoring force of the beam. As a result, the beam remains stuck to the substrate, rendering the MEMS device unusable.

Stiction may occur during fabrication of a MEMS device. For example, stiction may occur when a sacrificial layer used to temporary support the beam during fabrication is removed to release the beam. The sacrificial layer is often removed using a wet enchant followed by a rinse with a liquid agent, e.g., deionized (DI) water and/or methanol. As the device dries, liquid agent trapped between the beam and the substrate may produce capillary forces sufficient to pull down the beam into intimate contact with the substrate. Stiction may also occur during operation of a MEMS device, sometimes referred to as "in-use" stiction. For example, stiction may occur in a MEMS capacitor when the electrostatic force used to vary the capacitance of the MEMS capacitor pulls down the beam into intimate contact with the substrate.

Several approaches have been developed to alleviate stiction. One approach is to provide a rough surface on the substrate underlying the beam to reduce adhesion forces between the beam and the substrate. This is commonly done by depositing a nitride layer onto the substrate and wet etching grain boundaries in the nitride layer to produce a rough surface. A drawback of this approach is that "pin-holes" sometimes form in the nitride layer, which can lead to premature breakdown of the device. Another approach is to provide "dimples" or small bumps on the bottom surface of the beam to prevent the beam from coming into intimate contact with the substrate. A drawback of this approach is that it involves a cumbersome fabrication process that requires a planarization step, which may not be feasible in some process flows. Yet another approach is to use hydrophobic monolayers known as self assembled monolayers or SAM

coatings to make the beam hydrophobic. This reduces the likelihood that water droplets will form under the beam and pull the beam down into intimate contact with the substrate.

SUMMARY OF THE INVENTION

The present invention alleviates stiction between a suspended beam or microstructure and an underlying substrate by providing a patterned passivation layer on the substrate underneath the beam. The passivation layer is patterned to provide a substrate surface that differs substantially from the bottom surface of the beam. The difference between these two surfaces reduces the potential contact area between the beam and the substrate when the beam is pulled down, thereby reducing adhesive forces between the beam and the substrate and the likelihood of stiction.

In one embodiment, a bottom electrode is provided on the substrate to form a variable MEMS capacitor with the suspended beam acting as the top electrode of the MEMS capacitor.

In another embodiment, the passivation layer is patterned to form a substrate surface comprising a plurality of protuberances.

In still another embodiment, the passivation layer is patterned to form a substrate surface having a mesh pattern.

In yet another embodiment, a bottom dielectric layer is provided between the patterned passivation layer and the substrate.

Other objects and features of the present invention will become apparent from consideration of the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a MEMS structure comprising a patterned passivation layer for alleviating stiction according to an embodiment of the invention.

Figure 2 shows a MEMS capacitor comprising a bottom electrode underneath the patterned passivation layer according to another embodiment of the invention.

Figure 3A is a top view of a passivation layer patterned into a plurality of square protuberances.

Figure 3B is a top view of a passivation layer patterned into a plurality of rectangular protuberances.

Figure 3C is a top view of a passivation layer patterned into a plurality of hexagonal protuberances.

Figure 3D is a top view of a passivation layer patterned into a [square] mesh. *hexagonal*

Figure 3E is a top view of a passivation layer patterned into a [hexagonal] mesh. *square*

Figure 3F is a top view of a passivation layer patterned into a checkerboard mesh.

Figures 4A-4K show a process flow for fabricating the MEMS structure of Figure 1 according to an embodiment of the invention.

Figures 5A-5H show a process flow for fabricating the MEMS capacitor of Figure 2 according to another embodiment of the invention.

Figure 6 shows a MEMS structure comprising a bottom dielectric layer underneath the patterned passivation layer according to an embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

Referring to Figure 1, a MEMS structure [10] according to an embodiment of the invention

is shown. The MEMS structure 10 comprises a substrate 15, a passivation layer 20 on the

substrate 15, and a beam 25 suspended above the substrate 15. The substrate 15 may be made of

silicon, MgO, Alumina, quartz, Gallium Arsinide (GaAs), or other suitable material. The

passivation layer 20 may be made of a dielectric material, including, but not limited to, Silicon

Nitride (Si_3N_4), Silicon Oxide (SiO_2), Strontium Titanate Oxide ($SrTiO_3$), polyimide, Barium

Strontium Titanate (BST), and Benzocyclobutene (BCB). The beam 25 is suspended above the

substrate 15 by two anchors 30 attached to each end of the beam 25. Alternatively, the beam 25

may be supported by a single anchor attached to one of its ends. The beam 25 may be made of a

metal characterized by excellent flexibility, a high electrical conductivity and ease of deposition

or may be made of other conductive material such as doped polysilicon. Suitable metals for the

beam 25 include, but are not limited to, gold and silver. For RF applications, a low loss metal is

preferred.

To alleviate stiction between the beam 25 and the substrate 15, the passivation layer 20

underlying the beam 25 is patterned to provide a substrate surface that differs from the bottom

surface 27 of the beam 25. In the illustrative example in Figure 1, the bottom surface 27 of the

beam 25 is substantially flat, while the passivation layer 20 is patterned to form a substrate

surface comprising a plurality of spaced protuberances 40. The difference between these two

surfaces reduces the potential contact area between the beam 25 and the substrate 15 when the

beam 25 is pulled down, thereby reducing adhesive forces between the beam 25 and substrate 15

and the likelihood of stiction.

Subar (handwritten annotation)

Referring to Figure 2, a variable MEMS capacitor according to an embodiment of the invention is shown. The MEMS capacitor is similar to the MEMS structure in Figure 1, but further comprises a bottom electrode 115 on the substrate 20 and underneath the patterned passivation layer 20. The MEMS capacitor also comprises contact electrodes 120 on the substrate 20 and underneath at least one of the anchors 30. The electrodes 115, 120 may be made of metal, High Temperature Superconductor (HTS) material or other conductive material. In this embodiment, the suspended beam 25 acts as a top electrode of the MEMS capacitor. The gap and dielectric material (i.e., passivation layer 20) between the beam 25 and the underlying bottom electrode 115 determines the capacitance of the MEMS capacitor. The capacitance of the MEMS capacitor is varied by varying a bias voltage applied to the capacitor. The applied bias voltage establishes an electrostatic force on the beam 25 that bends the beam 25 relative to the bottom electrode 115, thereby varying the gap between the beam 25 and the bottom electrode 115. This is turn varies the capacitance of the MEMS capacitor. The passivation layer 20 overlying the bottom electrode 115 is patterned into a plurality of spaced protuberances 40 to alleviate stiction, e.g., "in use" stiction associated with electrostatic pull down of the beam 25.

Referring to Figures 3A-3F, the top view of patterned passivation layers 20 according to several embodiments of the invention are shown. In each of these embodiments, the passivation layer 20 is patterned to provide a substrate surface that differs from the flat bottom surface 27 of the beam 25 to alleviate stiction. Figures 3A-3C show the passivation layer 20 patterned into a plurality of protuberances 40 having square, rectangular, and hexagonal cross sections, respectively. Spacing the protuberances 40 far apart reduces the potential contact area between the substrate 15 and the beam 25 and, therefore, reduces the likelihood of stiction. In addition, spacing the protuberances 40 far apart reduces the fill-factor of the passivation layer 20, which

reduces the lossiness of the passivation layer 20 when used, e.g., in a MEMS capacitor for high

frequency applications. Spacing the protuberances too far apart, however, may allow portions of

the beam 25 to bend down between adjacent protuberances 40 and make contact with the

underlying substrate 15. Figure 3D-3F show the passivation layer patterned into a hexagonal

mesh, a square mesh, and a checkerboard mesh, respectively. Each of these mesh patterns may

be formed by selectively etching voids 130 into the passivation layer 20. For example, the

checkerboard mesh in Figure 3F may formed by etching square voids 130 into the passivation

layer 20 in a checkerboard pattern. The patterns shown in Figures 3A-3F are for illustrative

purposes and are not intended to be exhaustive.

Figures 4A-4K show an exemplary process flow for fabricating the MEMS structure of

Figure 1 according to one embodiment. In Figure 4A, a substrate 15 is provided. In Figure 4B, a

passivation layer 20 is deposited onto the substrate 15. In Figure 4C a patterning layer 150, e.g.,

photoresist, is deposited onto the passivation layer 20. In Figure 4D, the patterning layer 150 is

patterned to have the desired pattern for the passivation layer 20. The pattern may be any one of

the patterns shown in Figures 3A-3F or another pattern. The patterning layer 150 may be

patterned using photolithography, selective laser etching, e-beam writing and the like. In Figure

4E, the pattern of the patterning layer 150 is transferred to the passivation layer 20 by etching the

passivation layer 25 with an etchant, e.g., KOH, that selectively etches away the portions of the

passivation layer 20 exposed by the patterning layer 150. In Figure 4F, the patterning layer 150

is removed, e.g., using acetone.

Alternatively, the passivation layer 20 may be patterned directly without the use of the

patterning layer 150. For example, the passivation layer 20 may be made of a photo-imagable

material, e.g., Benzocyclobutene (BSB), that can be patterned directly using UV light. In this

example, the passivation layer 20 is patterned by exposing the passivation layer 20 to UV light through a photo mask (not shown) having the desired patterned and then selectively etching away portions of the passivation layer 20 exposed to the UV light, thereby transferring the pattern of the photo mask onto the passivation layer 20.

In Figure 4G, a sacrificial layer 160 is deposited onto the patterned passivation layer 20. The sacrificial layer 160 is used to provide mechanical support for the beam 25 and the associated anchors 30 during fabrication. The sacrificial layer 160 may be any suitable material, e.g., a photoresist, a polyimide or an oxide. In Figure 4H, the sacrificial layer 160 is patterned to form vias 165 in the sacrificial layer 160. At this stage in the process, the top surface of the sacrificial layer 160 may follow the contours of the patterned passivation layer 20, as illustrated in Figure 4H. This is undesirable because the top surface of the sacrificial layer 160 will later define the bottom surface of the beam 25. In order to obtain a smoother bottom surface for the beam 25, the top surface of the sacrificial layer 160 is smoothed out by subjecting the sacrificial layer 160 to a hard bake at a sufficiently elevated temperature, e.g., at 200° C. The hard bake initially lowers the viscosity of the sacrificial layer 160, causing the top surface of the sacrificial layer 160 to re-flow and smooth out, as illustrated in Figure 4I. The sacrificial layer 160 then hardens as moisture in the sacrificial layer 160 is evaporated. The re-flow process may also smooth the corners of the vias 165, which is not illustrated in Figure 4I. In Figure 4J, a metal or polysilicon layer 170 is deposited onto the sacrificial layer 160 and the vias 165. The metal layer 170 may be deposited using electroplating, sputtering, or e-beam deposition. In Figure 4K, the metal layer 170 is patterned to form the beam 25 and the anchors 30, and the sacrificial layer 160 is removed to release the beam 25 above the substrate 15. The sacrificial layer 160 may be removed using suitable means, e.g., wet etching the sacrificial layer 160 followed by a rinse with

a liquid agent, e.g. deionized (DI) water or methanol. The patterned passivation layer 20

alleviates stiction associated with the liquid agent, thereby increasing the production yield of the

MEMS device.

5A-5H show an exemplary process flow for fabricating the MEMS capacitor of Figure 2.

In Figure 5A, a substrate 15 is provided. In Figure 5B, a conductive material is deposited onto

the substrate and patterned to form a bottom electrode 115 and two contact electrodes 120. In

Figure 5C, a passivation layer 20 is deposited onto the substrate 15. In Figure 5D, the

passivation layer 20 is patterned to form spaced protuberances 40 over the bottom electrode 115

and vias 175 above the contact electrodes 120. The passivation layer 20 may be patterned using

a patterning layer (not shown) or may be patterned directly using a photo-imagable material for

the passivation layer 20. In Figure 5E, a sacrificial layer 180, e.g., photoresist, is deposited onto

the passivation layer 20. In Figure 5F, the portions of the sacrificial layer 180 corresponding to

the vias 175 in the passivation layer 20 are etched away. In Figure 5G, the sacrificial layer 180

is subjected to a hard bake to smooth out the top surface of the sacrificial layer 180. In Figure

5H, a metal or polysilicon layer is deposited onto the sacrificial layer 180 and patterned to form

the beam 25 and anchors 30 of the MEMS capacitor. In addition, the sacrificial layer 180 is

removed to release the beam 25 above the substrate 15.

Figure 6 shows a MEMS structure according to another embodiment. The MEMS

structure is similar to the MEMS structure of Figure 1, but further comprises a bottom dielectric

layer 250 on the substrate 15 and underneath the patterned passivation layer 20. The MEMS

structure according to this embodiment may be used to form a MEMS capacitor, e.g., by placing

a bottom electrode (not shown) on the substrate 15. The dielectric layer 250 may be polyimide,

silicon nitride or other oxide. The dielectric layer 250 may be deposited onto the substrate using

standard MEMS fabrication methods. To prevent the dielectric layer 250 from being etched during patterning of the overlying passivation layer 20, the dielectric layer 250 may be solidified before deposition of the passivation layer 20. This may be done, e.g., by exposing the dielectric layer 250 to UV light followed by a hard bake.

While various embodiments of the application have been described, it will be apparent to those of ordinary skill in the art that many embodiments and implementations are possible that are within the scope of the present invention. For example, even though the patterned passivation layer was described in the context of alleviating stiction between a beam and a substrate, the patterned passivation layer may be used to alleviate stiction between any microstructure and a substrate or between two adjacent microstructures, e.g., by forming the patterned passivation on one of the two adjacent microstructures. Therefore, the invention is not to be restricted or limited except in accordance with the following claims and their equivalents.